

Nuclear pasta structure in hot neutron stars

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Abstract. Structure of cold and hot dense matter at subnuclear densities is investigated by quantum molecular dynamics (QMD) simulations. Obtained phase diagrams show that the density of the phase boundaries between the different nuclear structures decreases with increasing temperature due to the thermal expansion of nuclear matter region.

At subnuclear densities, nuclear matter exhibits the coexistence of a liquid phase with a gas phase. Just below the density where nuclei melt into uniform matter, it is expected that, at sufficiently low temperatures ($T \ll 1$ MeV), the energetically favorable configuration of the mixed phase possesses interesting spatial structures such as rodlike and slablike nuclei, etc., which are called nuclear “pasta” (Hashimoto, Seki, & Yamada 1984; Ravenhall, Pethick, & Wilson 1983). While nuclear “pasta” at zero temperature is studied by several authors, “pasta” phases at finite temperatures relevant to supernova cores and crusts of young hot neutron stars have not been studied yet except for some limited cases (Lassaut et al. 1987; Watanabe, Iida, & Sato 2000, 2001, 2003).

In the present work, we study the structure of hot dense matter at subnuclear densities by QMD. Simulations of the (n, p, e) system at proton fraction $x = 0.3$ and 0.5 are performed with 2048 nucleons in a cubic periodic box. The relativistic degenerate electrons are regarded as a uniform background and the Coulomb interaction is calculated by the Ewald method. The effective Hamiltonian used in this work is that developed by Maruyama et al. (1998).

We show the resultant phase diagram for $x = 0.5$ on the nucleon density ρ vs temperature T plane in Fig. 1. Phase separation line is determined by disappearance of the long-range correlation of the nucleon distribution detected by the two-point correlation function. Nuclear surface is identified by plateau of the Euler characteristic density χ/V as a function of threshold density for isodensity surface. In the density region of interest, nuclear surface cannot be observed typically at $T \gtrsim 3$ MeV, even in the phase-separating region. At temperatures where nuclear surface can be identified, we characterise the nuclear shape changes with increasing the density by using averaged mean curvature

$\langle H \rangle$ and χ/V : (a) $\langle H \rangle > 0$, $\chi/V > 0 \rightarrow$ (b) $\langle H \rangle > 0$, $\chi/V = 0 \rightarrow$ (c) $\langle H \rangle > 0$, $\chi/V < 0 \rightarrow$ (d) $\langle H \rangle = 0$, $\chi/V = 0 \rightarrow$ (e) $\langle H \rangle < 0$, $\chi/V < 0 \rightarrow$ (f) $\langle H \rangle < 0$, $\chi/V = 0 \rightarrow$ (g) $\langle H \rangle < 0$, $\chi/V > 0 \rightarrow$ uniform. Critical point for the phase separation locates at $\rho \sim 0.25\rho_0$ and $T \gtrsim 6$ MeV. It is noted that the density of each phase boundary between the different structures decreases as T increases, which is due to the thermal expansion of the nuclear matter region.

Our result suggests that the “pasta” phases, and in addition, “spongelike” phases with negative values of χ/V exist in hot neutron star crusts and supernova cores at $T \lesssim 3$ MeV.

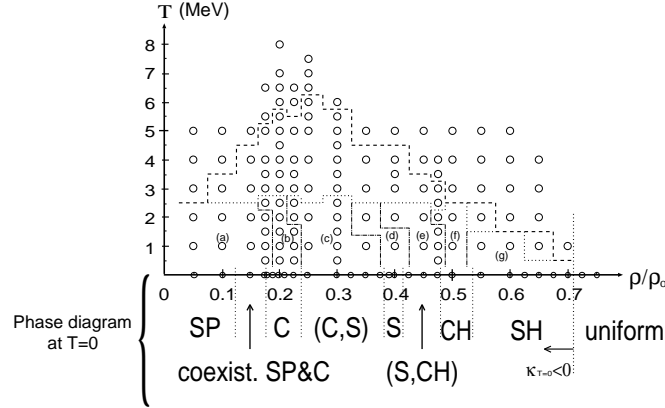


Figure 1. Phase diagram at $x = 0.5$. The dashed and the dotted lines on the diagram show the phase separation line and the limit below which the nuclear surface can be identified, respectively. The dash-dotted lines are the phase boundaries between the different nuclear shapes. The symbols SP, C, S, CH and SH stand for nuclear shapes, i.e., sphere, cylinder, slab, cylindrical hole and spherical hole, respectively. The parentheses (A,B) show “spongelike” intermediate phases between A and B-phases suggested in our previous works at $T = 0$ (Watanabe et al. 2002, 2003). They have negative χ/V . Simulations have been carried out at points denoted by circles. For regions (a)-(g), see text.

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